

# A NEW PROTON CT DETECTOR

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## ABSTRACT

The design, construction, and preliminary testing of a 2<sup>nd</sup> generation proton CT scanner is presented. All current treatment planning systems at proton therapy centers use x-ray CT as the primary imaging modality for treatment planning to calculate doses to tumor and healthy tissues. One of the limitations of x-ray CT is in the conversion of x-ray attenuation coefficients to relative (proton) stopping powers, or RSP. This results in more proton range uncertainty, larger target volumes and therefore, more dose to healthy tissues. To help improve this, we present a novel detector capable of high dose rates, up to 2 MHz, and large area coverage, 20 x 23 cm, for imaging an adult head phantom and reconstructing more accurate RSP values.

## INTRODUCTION

Northern Illinois University in collaboration with Fermi Nat'l Accelerator Laboratory (FNAL) has been designing and building a proton CT detector, or scanner, for applications in proton treatment planning. In proton therapy, the current treatment planning systems are based on x-ray CT images that have intrinsic limitations in terms of dose accuracy to tumor volumes and nearby critical structures. Proton CT aims to overcome these limitations by determining more accurate relative proton stopping powers (RSP) directly as a result of imaging with protons. At present, the proton stopping powers for various tissues, as derived from x-ray CT, produce range uncertainties<sup>1</sup> of about 3 to 4%. We hope to reduce this to approximately 1% of the total range using proton CT. In addition, three to five times lower doses than X-ray CT are possible and absence of artifacts from high density dental or other implants will add to higher quality images. To this end a new proton CT scanner is being built to acquire head size images with scan times below 10 minutes. Since individual proton tracks and their energy loss must be measured through the patient, the data rate must be of order 2 MHz to acquire of order 1 billion tracks in under 10 minutes. To this end, a new proton CT scanner has been developed at Northern Illinois Univ. in conjunction with FNAL in Batavia, IL.

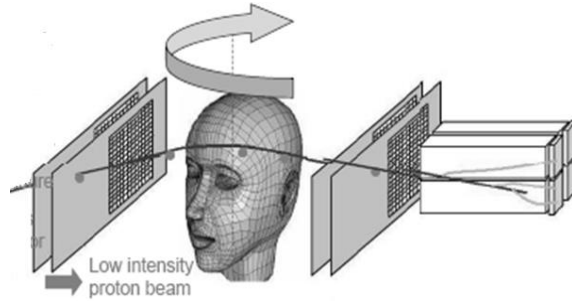


Fig.1 Four (X,Y) stations measure the proton trajectory before and after the patient. A calorimeter is used to measure the residual energy after the patient. The segmented CsI calorimeter shown here has been replaced with a stack of 3.2 mm thick scintillator tiles as described in the text. Figure courtesy of Reinhard Schulte, LLUMC.

Fig. 1 shows a schematic of a proton CT scanner. It consists of eight planes of tracking detectors; two X and two Y coordinate measurements both before and after the patient. This provides the maximum information for finding the trajectory through the body since some deflection, of order 3 or 4 mm (rms), will occur due to multiple coulomb scattering. A “most likely path” formalism, or MLP, developed by Erdelyi<sup>2</sup> is used to find which voxels, of order 1 mm<sup>3</sup>, are crossed by every track. This information as well as the integrated energy loss measured in a calorimeter is used by the image reconstruction software to generate 3D maps of RSP values in each voxel of the patient.

## DESIGN SPECIFICATIONS

In addition to a high data rate of 2 MHz, we wish to cover a large enough area to image an adult human head so that table motion is not required or that we do not need to splice data from multiple scans to make an image long enough along the body axis. For head scans, we have chosen a maximum head size of 23 cm diameter and a length along the body axis of 20 cm for imaging. This will allow imaging from the crown of the head down to the jaw bone in one 360°, or even one 180° gantry rotation for most patients. A fixed incident proton beam energy of 200 MeV with a range of 26 cm can be used for head size imaging.

Given that this scanner, or one like it, will likely be mounted on a proton treatment gantry, one can make use

of the cone beam geometry of proton beam delivery systems which generate their large fields either by use of scanning magnets or double scattering systems. In either case, there is an effective divergence point, or points, of the beam that is 2 to 2.5 m upstream of the target. This cone beam geometry and the size of the imaging target sets the size of the tracking planes and calorimeter. Due to the significant amount of multiple coulomb scattering in the tracker planes at these low energies, 50 to 200 MeV, it is necessary to reduce the mass of the tracker planes as much as possible to minimize errors in reconstructing the proton path through the patient.

## DETECTOR DESIGN AND CONSTRUCTION

In order to have low mass detectors, with high proton rates, and continuous area coverage over a large area, the tracker was constructed from 0.5 mm diameter polystyrene scintillating fibers by Kuraray<sup>3</sup>. Fibers were cut to 20 to 30 cm length, then laid flat, and doubled layered ( see fig. 2) on a low density ,0.03 g/cm<sup>3</sup>, 2 mm thick rohocell substrate with machined grooves and glued to hold the fibers in place with close spacing to avoid gaps in detecting passing protons. The entire assembly is supported on Techtron (carbon fiber) frames. A photograph of one tracker plane, 20 x 24 cm, is shown in Fig. 3. Fibers are grouped in triplet, called bundles, according to Fig. 2 which give a pitch between bundles of 0.92 mm. Each bundle is readout into Silicon photo multipliers (SiPMs), produced by CPTA<sup>4</sup> which are mounted on blocks that connect each of them to a fiber triplet. The SiPMs chosen have the best chromatic (or wavelength) match to the Kuraray scintillators. One end of each fiber is polished with an applied reflective coating and the other end is polished and mechanically pressed to an SiPM on a block shown in Fig. 3b. The rms spatial resolution of each tracker plane is given by the pitch divided by  $\sqrt{12}$ , or 0.26 mm. The integrated water equivalent thickness (WET) of each tracker along the beam direction is less than 1 mm. With 4 planes of 20 x 24 cm area and 4 planes with 24 x 30 cm area, there are about 2100 channels of readout for the entire tracker.

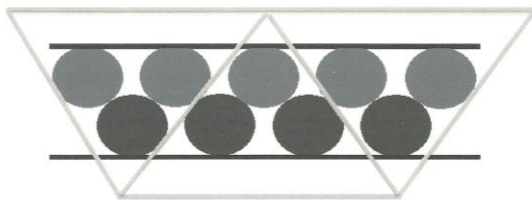


Fig. 2. The double layer configuration of fibers which are bundled into triangular triplets for readout through a single SiPM. Spacing between bundles is 0.92 mm.

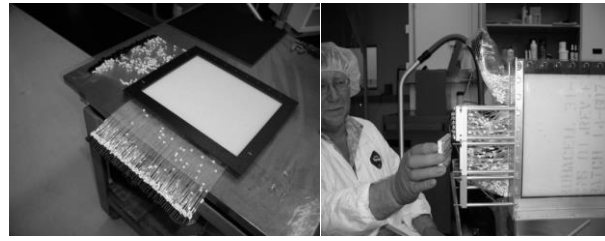


Fig. 3a and 3b. An (X,Y) fiber tracker station assembled on 2 mm rohocell substrate. The fiber ends are attached to SiPMs through an interface board shown on right side.

The calorimeter chosen for this design is a proton range detector which consists of a stack of 96, 3.2 mm thick, poly vinyl toluene (PVT) scintillating tiles, with 0.1 mm aluminized mylar between adjacent tiles. Each tile, 27 x 36 cm area, is machine grooved to embed a 1 mm diameter wavelength shifting fiber that weaves 4 times across the tile for improved light collection efficiency. Both ends of the WLS fiber are read out through SiPMs to capture more light. This requires 192 channels of readout for the calorimeter. Each SiPM signal is amplified and digitized for later analysis for fitting to the shape of a Bragg peak to determine the proton range in the calorimeter. Since the water equivalent range of the patient plus calorimeter is a constant, the calorimeter range measurement can be used to determine the water equivalent path length (WEPL) in the patient. While it is more accurately determined from a calibration procedure<sup>5</sup>, this quantity is what is needed for the image reconstruction program.

An intrinsic limitation in any proton calorimeter is the combined range (or energy) straggling of the patient plus calorimeter. The combined mass of patient plus calorimeter is equal to the mass ( g/cm<sup>2</sup>) required to stop incident 200 MeV protons. In water equivalent materials, such as ours, the range straggling of an individual 200 MeV proton in water equivalent materials is +/- 3.6 mm, rms<sup>6</sup>. Therefore, there is little incentive to produce tiles less than 3 mm thickness.

The 96 tile calorimeter has been built and under gone first test with 200 MeV proton beam at the ProCure Proton Treatment Center at Central DuPage Hospital in Warrenville, IL. A photo of the calorimeter is shown in Fig. 4 and the first results of Bragg peak measurement for a 200 MeV proton beam measuring 9000 protons is shown in Fig. 5.

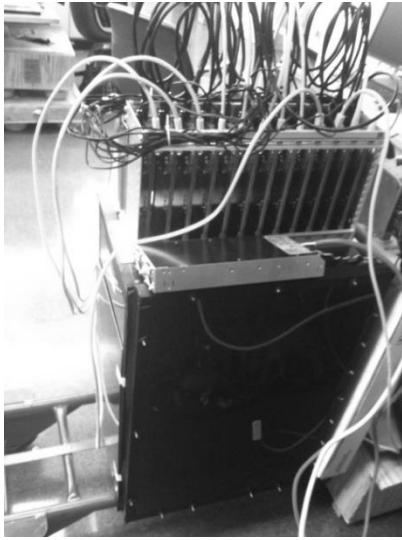


Fig. 4. The 96 tile calorimeter. 192 SiPMs in 8 electronics modules containing amplifiers and ADCs are attached on the top side in this photo. Beam enters horizontally from the left through the tiles in a black, light tight enclosure.

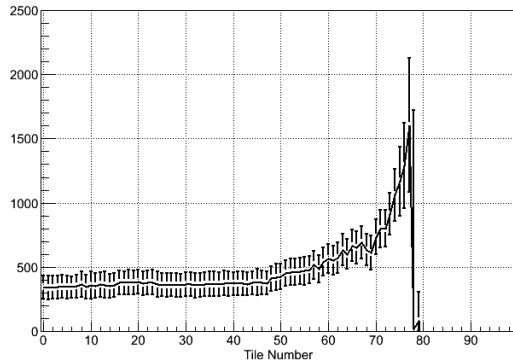


Fig. 5. First Bragg curve measurements using 200 MeV mono-energetic protons stopping in 96 tile range stack of 3.2 mm thick PVT scintillating tiles. The y-axis is the average ACD counts in each tile for 9000 proton histories with 15 ADC counts per photo-electron.

## ELECTRONICS

The electronics that reads out the SiPMs consists of a custom board with preamplifiers, digitizers, and ethernet readout (PAD-E in Fig. 6). This custom board uses COTS components to provide readout for up to 32 channels of SiPM in a 220mm x 100mm format that fits into a standard 3U sub-rack. The same board is used for readout of the trackers and the calorimeter. The digitization of the signals from SiPMs, after appropriate amplification and shaping, is 12 bits per channel at 75MSPS. The PAD-E is completely self contained and generates the bias for the SiPMs (one bulk voltage but with a 3V adjustment range for each SiPM). It also contains an FPGA for processing all of the data generated by the SiPMs, memory for

buffering up to 128MB of data and a gigabit ethernet interface for pushing data directly to the DAQ. Other support circuitry includes temperature sensors for the SiPMs, clock management and a high speed USB port for debugging. Parameters such as the boards' ethernet address or the correct bias voltage for the SiPMs are stored in a small FLASH memory on the board. The PAD-E is powered by a single 5V power supply (via a 48V distribution scheme) and has a power consumption of up to 15W for 32 SiPMs. There is no backplane in the system- boards which are connected to each other via high speed LVDS link for clock distribution. Each board locks to the clock provided by one board in each of the 9 sub-racks. Each of these boards in turn locks to a "master" board (just one of the PAD-Es) which has a free running crystal clock. Run control is accomplished by communicating with this "master" over ethernet. The scanner is "self triggered" in the sense that any channel with a signal above threshold will be time stamped and stored in a local buffer for readout. A synchronous signal allows all boards to provide a timestamp that is used by the DAQ system to associate the data from different parts of the detector for a single proton history. Data from signals in the detector is highly compressed (only fiber address and timestamp from the trackers, compressed amplitude and time stamp from the calorimeter) and sent to the DAQ as soon as it is available. A synchronization signal which circulates across all boards approximately once per millisecond allows data taking to pause very briefly while all data buffers are flushed, if necessary and a footer is sent to the DAQ. Organizing the data into these one millisecond "time frames" allows the for a relatively small timestamp (16 bits of 75Mhz clock cycles) and allows the DAQ to monitor the integrity of the data flow and to recover from any transient errors without ambiguity.

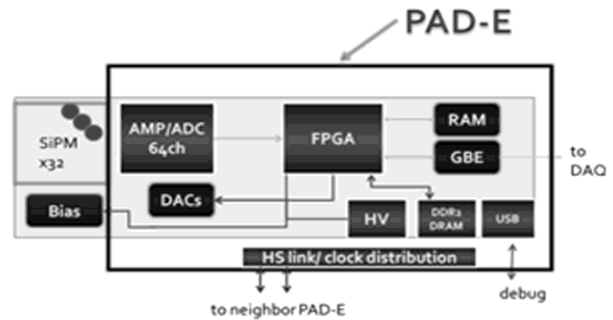


Fig. 6. A diagram of the front end electronics (PAD-E) for amplifying, digitizing and storing data before shipping to the DAQ at one millisecond intervals .

## DATA ACQUISITION SYSTEM

The structure of the DAQ system for the pCT scanner is shown in Fig. 7. The front end electronics will send data to the DAQ via 1 Gbit/s ethernet lines using UDP protocol. Each proton event contains data for 8 tracker planes and the 96 tile scintillator stack. We calculate that each proton event will generate about 25 bytes from the 8 hits on the 8 planes and about 75 bytes from the 96 tile range detector. For a 10 minute scan with 90 projection angles at a data rate of 2 million protons per second, we expect 200 MB/sec written to RAM by 24 data collectors running on 6 interconnected Linux workstations ( by Silicon Mechanics). At the end of the scan, the back end DAQ will write data to disk and subsequently, through post processing of the data, obtain proton histories in the format for image reconstruction, i.e., 4 X and 4 Y coordinates, proton range, and beam projection angle.

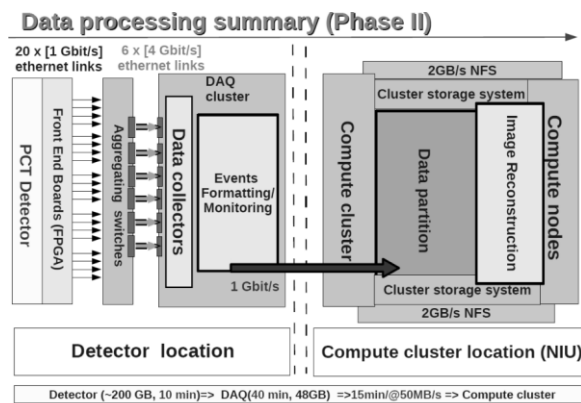


Fig. 7. The DAQ architecture for proton CT. Data collectors hold hit locations and ADC amplitudes of the scintillator tiles with a time stamp for coalescing into tracks during post processing. Bonafide events are then sent to the image reconstruction computer cluster shown on the right side of the figure.

## FUTURE WORK

The NIU Phase 2 proton CT scanner is coming together well with expected completion date in October 2013. The calorimeter has been fully assembled with first test in a 200 MeV proton beam in Warrenville, IL, USA. A water equivalent range of 26 cm was verified with position of the Bragg peak in tile number 77. Additional development is required to complete the FPGA coding to allow synchronization, i.e. time stamping, of hits from various detector modules after readout to the DAQ. A high performance CPU/GPU cluster<sup>7</sup> has been installed and

tested at NIU (see Fig. 7) for image reconstruction from beam data taken at Loma Linda Univ. Med. Ctr. The scanner will be mounted on a cart along with a rotatable phantom for insertion into a horizontal beam. After a series of calibration tests performed at our local facility, Central DuPage Hospital, we will mount a CIRS head phantom<sup>8</sup> onto the rotation stage for the first 3D head scan in winter or early spring of 2014.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] U. Schneider, "Proton Radiography as a tool for quality control in proton Therapy," *Med. Phys.* 22, p.353 (1994).
- [2] B. Erdelyi, "A comprehensive study of the most likely path formalism for proton computed tomography," *Physics in Medicine and Biology* 54, p.6095 (2009).
- [3] KurarayCo.,Ltd,Japan, <http://kuraraypsf.jp/psf/index.html>
- [4] ICPTA Ltd., Moscow, Russia, [www.cpta-apd.ry](http://www.cpta-apd.ry)
- [5] R.F. Hurley et. al., "Water equivalent path length calibration of a prototype CT scanner," *Med. Phys.* 39 (5), p. 2438 (2012).
- [6] J. Janni, "Proton range-energy tables, 1keV- 10GeV," *Atomic Data and Nuclear Data Tables* 27(2-5), p.147-429 (1982).
- [7] K. Duffin et. al., "An analysis of a distributed GPU implementation of proton computed tomographic reconstruction", *Proceedings of the 2012 Super Computing Companion: high performance computing, networking storage and analysis*, pg.166-175, ISBN no. 978-0-7695-4956-9, Nov. 2012, Seattle, WA.
- [8] Computerized Imaging Reference Systems, Inc, Norfolk, VA, [www.cirsinc.com](http://www.cirsinc.com)